

# Simulation of PMV and PPD Thermal Comfort Using EnergyPlus

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**Abstract.** This work aims to simulate the thermal comfort for the user of a movie theater in the dimension related to considering the thermal environment parameters by the using EnergyPlus software. The results from simulation are then compared with the experimental ones. In order to calculate and model the thermal comfort, it was necessary a proper characterization of the space that included the measured occupancy, thermal environment variables, distinct electric equipment and lights. To compute the Predicted Mean Vote (PMV) and the Predictable Percentage of Dissatisfied (PPD) in EnergyPlus, the metabolic rate, air velocity and clothing insulation were defined according to the cinema specifications.

The results obtained from EnergyPlus were then compared with the experimentally measured ones. Minor differences were observed regarding the comfort sensation. Despite the differences, the variation in the percentage of dissatisfied people is smaller than 2%. Furthermore, this work also allowed verifying that the occupancy rate is a determining factor in the thermal comfort sensation and, in this case, people provided the necessary energy to heat the cinema room in the second session that occurred at night.

**Keywords:** Thermal comfort · Energy performance of buildings · Cinema · EnergyPlus

## 1 Introduction

The energy performance of a building and its relationship with the thermal environment plays a fundamental role in decision making from the point of view of the individual's comfort. It is a complex field that has been attracting the interest of many researchers [1]. The thermal environment represents a set of thermal variables that influence the heat exchanges between the individual and the environment in which it is inserted [2]. Yao et al. [3] mentioned that the thermal environment results from the complex interaction between the average radiant temperature, air temperature, air velocity and air humidity, referred to as environmental parameters.

People spend much of their time indoors, where many of these environments are air-conditioned and the equipment programming must be properly regulated, taking

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S. Misra et al. (Eds.): ICCSA 2019, LNCS 11624, pp. 52–65, 2019.
https://doi.org/10.1007/978-3-030-24311-1_4

into account the health, comfort and productivity of its occupants [4, 5]. When the thermal environment is not the most appropriate, individuals tend to adapt their behavior and expectations in order to adapt to that environment. They usually have a lower tolerance for the inadequacy of the thermal environment in air-conditioned spaces compared with naturally ventilated ones [6]. The physical effects caused by uncomfortable environments induce agitation, which can reduce attention and concentration, and lead to fatigue and drowsiness. The individual needs to maintain its internal temperature within very narrow limits at a temperature of approximately 37 ° C, which necessitates a constant search for thermal equilibrium, called homeothermy. This equilibrium is ensured whenever the heat produced by the organism is equal to the heat flow to the environment so that the temperature remains constant [7], ensuring the optimal operation of the main functions of the particular organism, the central nervous system.

Thermal neutrality can be attributed to the state of thermal comfort [8], provided that there is no local thermal discomfort (ISO 7330:2005), as this can be felt as a whole or in part of the body, as a result of asymmetries of radiant temperature, vertical temperature, air velocity, soil temperature and others. ASHRAE (2004) [9] defines thermal comfort as the mental state that expresses a man's satisfaction with the thermal environment that surrounds him; and whereas the ISO 7730:2005 defines it as an expression of satisfaction with the environment that surrounds the individual. According to Parsons [10], the environmental variables combined with the indexes of metabolic rate and clothing (designated by individual parameters), form the basic elements that define thermal comfort. There are numerous thermal comfort evaluation indices, however, a method developed by Fanger is, indeed, the most used in designing guides and standards [11]. The method is based on the theory of thermo-regulation and thermal equilibrium in 2 indexes, which are: PMV - Predicted Mean Vote; PPD - Predicted Percentage of Dissatisfied People or predictable percentage of dissatisfied. The PMV index represents the predicted mean vote in a 7-point thermal sensation scale, ranging from −3 (Very cold) to +3 (Very hot). The value of 0 represents a neutral sensation towards the thermal environment and thus a comfortable sensation. The PPD index is a complementary index to the PMV, indicating the predicted percentage of dissatisfied people. For a value of 0 for the PMV, the PPD takes its lowest value of 5% dissatisfied people. When the PMV values deviate from 0 (comfort position) either positively or negatively, the PPD value increases indicating a higher percentage of dissatisfied people.

In order to provide a good cinema experience, it is essential to guarantee the thermal comfort of the users. As of 31 December 2016, there were 549 cinema screens in Portugal, 192 of them in Multiplex venues (8 or more cinemas), with a total of 103,583 seats, of which 35,758 seats in venues with eight or more cinemas. In the year 2016 650,011 cinema sessions were shown, for a total of 14,890,813 spectators [12]. The rooms had an average of 187 seats, with an average occupancy rate of approximately 12%. Considering the average duration of TOP 10 movies most seen in 2016, 117 min, the sum of hours that the spectators spent inside the Portuguese cinemas will be around 29,037,085 h.

The cinema experience requires an environment technically prepared for this purpose, capable of providing the user with a surrounding that the latter cannot replicate in

other spaces. Watching a film in a movie theater results in the temporary occupation of an air-conditioned space for a certain period of time. A sensory experience, where the inadequacy of the thermal environment or another element such as; the sound, the lighting and others, can provoke interference and break the established tune between the spectator and the narrative.

In recent years, studying the optimum performance and understanding the energy consumption using numerical models has been an attractive option for researchers [13–20].

Yu et al. [13] developed a building energy consumption simulation through EnergyPlus. With this study, it was possible to understand and analyze the impact of the envelope heat consumption for different thermal performances and energy savings potentials.

Zhao et al. [14] optimized the energy consumption of a heating, ventilation and air conditioning system (HVAC) using an occupant-oriented mixed-mode EnergyPlus predictive control system, without forgetting the individual thermal comfort preference. With this work, it was possible to reduce the active HVAC energy consumption.

Pombeiro et al. [15] presented the formulation for three models that optimize the control of an HVAC system in an experimental room, which are coupled with two thermal models for the indoor temperature. Their results show that both the dynamic programming and genetic algorithms are capable of optimizing the usage of the HVAC.

Yun et al. [16] explored the role of occupants' perceived control in their subjective evaluation of thermal environments and its effects on cooling energy consumption in air-conditioned buildings. To do this, dynamic building energy simulations were conducted using EnergyPlus to examine the influence of perceived control on building energy consumption. With this study, it was possible to reduce the cooling energy consumption by 9% without sacrificing the thermal comfort of the occupants.

Cetin et al. [17] presented the development and validation of an on/off controller for residential applications in EnergyPlus using a custom EMS (energy management system). This on/off controller improves the HVAC energy use by around 19% in terms of the Normalized Mean Bias Error (NMBE) at the one-minute level compared to the results without the application of the on/off controller.

Ashrafian et al. [18] simulated two classrooms in order two understand the impact of different transparency ratios and window combinations in two critical orientations (west and east) on occupants' comfort and the energy demands of the classrooms. The referred authors concluded that reductions of 15-18% in electricity consumption can be obtained through appropriate design and the energy required for heating can be reduced by 8.5%.

Rincón et al. [19] examined an alternative low-cost earthen construction system using EnergyPlus. Results showed that the combination of night ventilation and roof solar protection in the high-inertia earthbag building leads to almost a total elimination of thermal discomfort during the year.

Escandón et al. [20] developed a surrogate model to speed up the thermal comfort prediction for any member of a building category, ensuring high reliability by testing the entire simulation process with real data measured in-situ. The model with high reliability reduced the computational times by 98% which is very useful to plan the energy retrofit of large housing stocks, by optimizing as quickly as possible.

The objective of this study is to calculate PMV and PPD using EnergyPlus simulation software and compare it with experimental results.

## 2 Methodology

### 2.1 Cinema Description

**Room.** The space under study is Room 2, presented in Fig. 1, of a cinema complex in Penafiel and began its activity in April 2014. The complex is composed by 3 cinema rooms with a total of 366 places. For the present study, the focus is in the largest room of this cinema complex, containing 170 seats; its capacity is the closest to the average capacity of 188 seats for the National Rooms.

The room does not have the means to allow the natural renovation of the air during the sessions of cinema, the air renovation is thus forced through the air conditioning equipment. The air supply is done through six points located on the ceiling of the room, and the extraction through holes under the chairs.

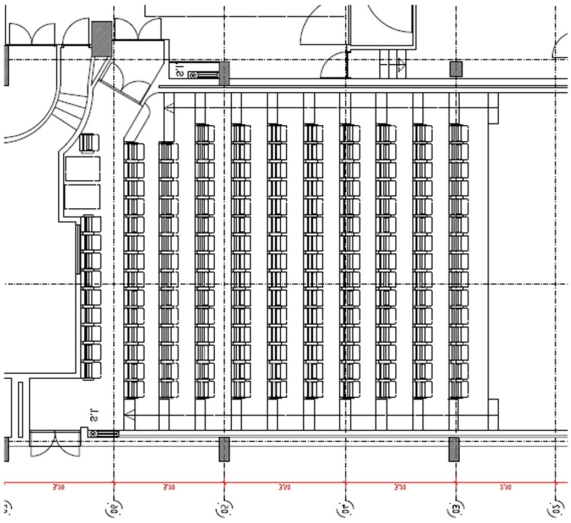


**Fig. 1.** Illustration of the cinema room plant.

**HVAC System.** The HVAC system is composed by an MCQUAY Model 75 19 equipment, which is installed next to the facade on the exterior of the building. This equipment does not have a system of air recirculation, thus all the air that enters the room is new air coming from the outside.

When the room occupancy surpasses, approximately, 25% of its capacity, the HVAC system is activated 10 to 15 min after the beginning of the session at a temperature of 22 °C. The equipment control unit is located outside the room, within the projection booth.

## 2.2 Field Measurements

**Occupancy.** In order to select the measurement points, the distribution of occupancy per seat was calculated based on the seats preference of the 6,041 tickets sold in the period between December 1, 2016, and January 31, 2017, for the study room. Due to material limitations, for this study only the following measurement points were chosen: B8, place with the highest occupancy rate (2.56%); K14, place with the lowest occupancy rate (0.08%) and G12, a place with the sample median (0.40%). Figure 2 represents the distribution of occupancy in the room floor plan.

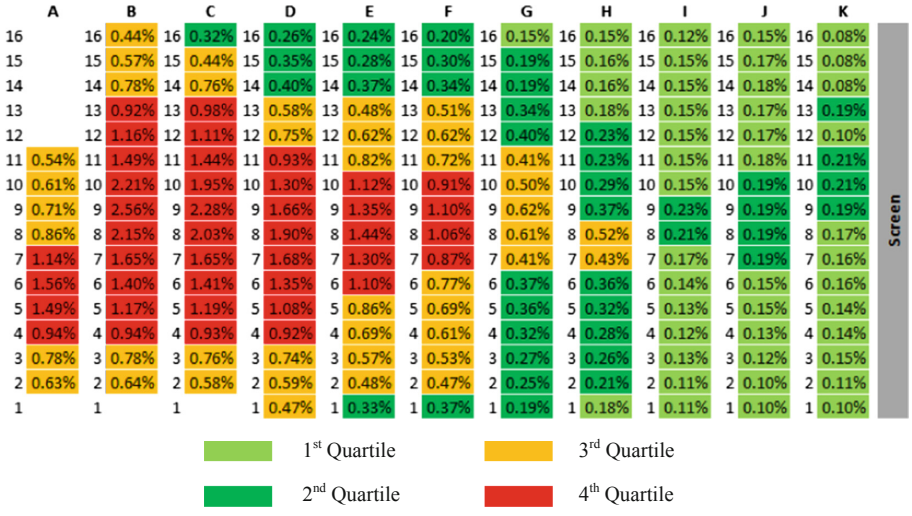



**Fig. 2.** Occupation and distribution in the cinema room.

**Environmental Characterization.** The characterization of the thermal environment of the studied space was done by means of experimental measurements in April 2017, in the previously selected points and in randomly chosen sessions. To measure the different variables in real time, it is necessary to use some instruments simultaneously, and its calibration has much relevance in the accuracy of the data obtained. For this study, the instruments were assigned by the Department of Production and Systems of the University of Minho, and there were no changes in their calibration.

For the experimental measurements, the following instruments were used:

- A globe thermometer, namely, a Casella model RS2842:1992, was used to measure the individual exposure to radiant heat. The device was placed at the chest level, on a tripod, to remain stable. A waiting period of about 30 min preceding the first measurement was necessary for stabilizing the device readings and assure data reliability. Results were collected every 15 min. The globe thermometer was also used to track down possible sources of radiant heat mentioned above;

- A TSI Velocicheck Model 8330 anemometer was used to measure air velocity. It was placed at chest level on a tripod so as to remain stable and not oscillated, waiting about 5 min before the first measurement was performed and results were collected every 15 min;
- Three USB Datalogger from Elcar, model EL-USB, to measure the temperature, relative humidity of the air and calculate the dew point. They were placed on a tripod at chest level and remained stable at that location during the measurement period. The equipment has been programmed in the "Easy Log" software to collect data every minute. Due to material limitations, it was not possible to place the instruments in more than one height level.

In the course of this study, it was important to record the temperature and relative humidity of the outdoor air at the time of the different measurements, since these two variables can affect the interior thermal environment and its perception [21]. For this purpose, the website of the Portuguese Institute of the Sea and Atmosphere was used since it registers the daily average temperature (°C) and relative humidity (%), as well as the minimum and maximum values for several climatological stations, measured at 1.5 m height. The data consulted were provided by the Climatological Station of Porto S. Gens and regarded the 19$^{th}$ of April 2017, when this study took place.

### 2.3 Simulation Study

The EnergyPlus is a powerful energy simulation software with a high potential for space analysis and improvement when compared with other software.

The types of energy analysis software like the EnergyPlus have wide application prospects. Many conclusions can be obtained through the simulation of the building energy consumption under different thermomechanical conditions.

The EnergyPlus is a simulation tool for modern buildings approved by the Portuguese Department of Energy. It is based on two tools developed during the 70s after the oil crisis: BLAST and DOE-2. The EnergyPlus is an Open Source code used worldwide. The software can model with excellent precision radiant and convection heat fluxes between indoor and outdoor, HVAC systems performance, heat exchanges with the ground, thermal comfort, natural, artificial and hybrid systems. Additionally, it can simulate ventilation, airflows and allows dynamic transient simulations with a time interval range between 1 h and 1 min, using an hourly representative year.

**3D Model.** The definition of the 3D model was based on the elements collected at the time of characterization of the space.

The geometry was modeled with Sketchupro2016 software associated with OpenStudio. The room was designed in two blocks. The first represents the upper part of the room where the occupation is made. The second block is the lower part of the room, through which the air is extracted and is an empty space (Fig. 3).

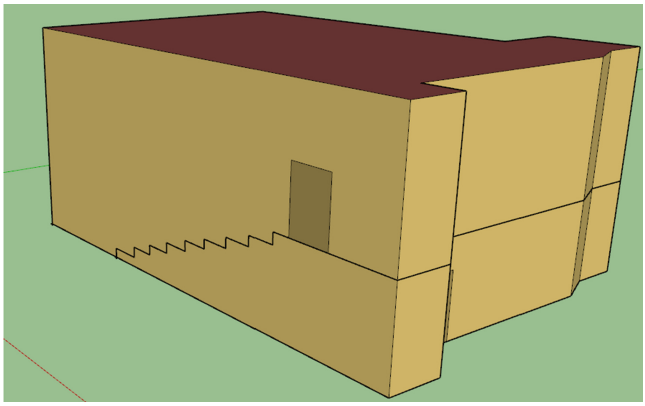


**Fig. 3.** Geometry of the movie theater.

The next step was the characterization of the surfaces of the model, according to exposure and location and boundary conditions. The South and East walls were considered as being exterior while the rest were defined as interior and considered as adiabatic surfaces. In Fig. 4 the exterior walls are in blue and the interior walls are in pink.

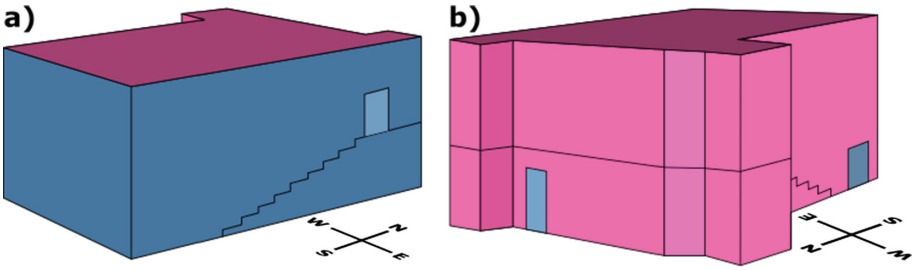



**Fig. 4.** Representation of the exterior walls at blue, (a) and the interior walls at pink (b). (Color figure online)

Although two different spaces were defined, they were assumed to belong to the same thermal zone in order to facilitate the simulation.

After the definition of the 3D model with the characteristics of the surfaces and the thermal zone, the model was extracted to the OpenStudio plugin that is connected to the EnergyPlus. It was decided to use OpenStudio because it has a friendlier and simpler interface than working directly with the EnergyPlus.

**Climate Data.** To obtain the values of PMV and PPD it is necessary to choose a climate file for the location where the cinema is located. The Climas-SCE1.05 software was used to obtain the reference Meteorological Year and the corresponding weather statistics. The software prepares the climate file for the format ".epw" (ESP-r/EnergyPlus Weather format) (Fig. 5).

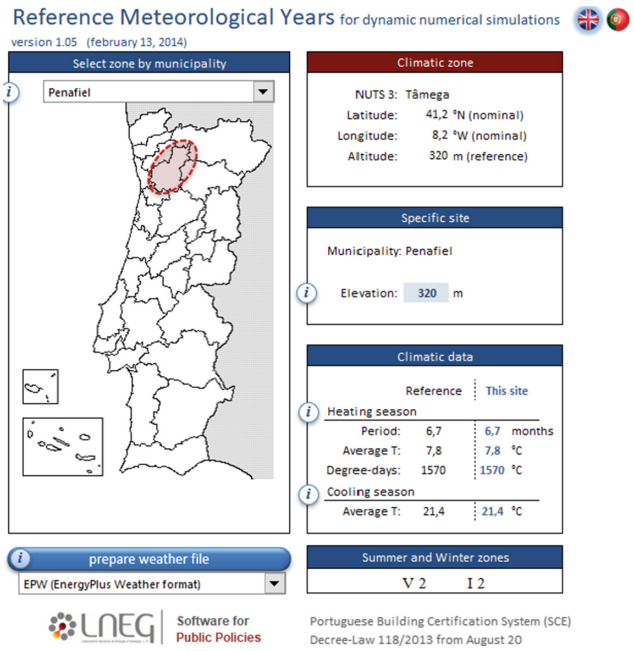



**Fig. 5.** Climas-SCE1.05 software.

**Schedules.** The schedules were defined for the whole year. The profiles of occupancy, air infiltration, activity level, ventilation and heating and cooling thermostat, lighting, electric equipment were thus constructed. First, daily profiles were built for weekdays, Saturday and Sunday. Then went on to build a weekly and monthly profile ending in the construction of the annual profile.

In the case of the activity level, taking into consideration that in the cinema people are in a sitting and resting state, the basal metabolic rate was assumed, namely, 105 W. Once that this situation does not vary, this value remained constant throughout the year.

In order to calculate the PMV and the PPD, work efficiency, air velocity and clothing schedules were also created. Taking into account the Air Changes per Hour required for the cinema occupation, a value of 0.25 m/s was assumed for air velocity. Regarding the clothing insulation, a value of 1 clo was chosen since it represented the standard clothing insulation for that time of the year. For the work efficiency, it was assumed a value of 0 since there was almost no mechanical activity and is safe to assume that almost all the metabolic energy was released as heat.

**Materials and Constructions.** In order to define the constructive elements, the constituent materials were defined in terms of roughness, thickness, conductivity, density and specific heat. Next, the layered constructions were created from the exterior surface to the interior surface and the ground contact surface. Table 1 presents the material properties considered in the EnergyPlus software.

**Table 1.** Material properties of the surface elements.

| | Thickness (mm) | Specific Heat (J/kg.K) | Conductivity (W/m.K) | Density (kg/m$^3$) |
|---|---|---|---|---|
| Exterior wall | 0.002 | 890 | 230 | 2700 |
| Interior wall (layer 1) | 0.02 | 1046 | 1.3 | 1900 |
| Interior wall (layer 2) | 0.11 | 960 | 0.407 | 875.5 |
| Interior wall (layer 3) | 0.02 | 1046 | 1.3 | 1900 |
| Exterior roof | 0.2 | 2350 | 0.818 | 940 |
| Ground | 0.2 | 2350 | 0.818 | 940 |

**Loads.** The loads are related to the settings of the number of people, lighting power and electric equipment. The cinema has a capacity for 170 people, 2,000 W of lighting power and 2 W/m$^2$ for electric equipment.

**HVAC System.** Considering that the information on the HVAC equipment was scarce, a system with ideal loads was used.

This mode is often used before the definition of the HVAC system to be installed. It has been defined that the system is 100% available from the moment the room is opened until the end of the last session.

**Cooling and Heating Thermostat Schedule.** For the normal daily profiles, the maximum temperature was considered as 28 °C and whenever the room opens at about 15:00, the cooling is set to a temperature of 23 °C.

For the normal operating period, a minimum temperature of 18 °C has been set while the room is closed, which is changed to 21 °C when opening the room.

**Output Variables.** Finally, the outputs of interest were defined, namely, Zone Thermal Confort Fanger Model PMV, Zone Thermal Confort Fanger Model PPD and Zone Mean Air Temperature.

## 3 Results and Discussion

### 3.1 Experimental Results

Experimental measurements were performed at a measurement point inside the room at the B8 seat, starting at 15:00 and ending at 20:30 on April 19, 2017. During this period there were two sessions of cinema, the first one began at 15:30 and the ended at 18:00, with an occupancy rate of 76.4%. The second one started at 18:50 and ended at 21.00, with an occupancy rate of 34.7%.

Table 2 summarizes the results for the measured variables, identifying the maximum, minimum, mean values and standard deviations of the obtained values for the first session.

**Table 2.** Experimental measurements results.

| | Max. | Min. | Avg. | Std. |
|---|---|---|---|---|
| Temperature (°C) | 24.5 | 20.0 | 22.2 | 0.9 |
| Dew point (°C) | 15.5 | 8.9 | 14 | 1.2 |
| Relative humidity (%) | 65 | 37 | 59.9 | 4.2 |

For the calculation of PPD and PMV indexes, the average metabolic value of a 70 kg man with a skin surface of 1.8 $m^2$ was used as a reference, sitting in a comfortable environment with 1 met (≈58.2 $W/m^2$), and 1 clo, which represents a typical indoor clothing combination during the winter. The values of the environmental parameters used to calculate the indexes were those recorded during the periods of the cinema sessions, with an interval of 15 min.

Table 3 summarizes the results for the calculated indexes, identifying the maximum, minimum and mean values.

**Table 3.** PMV and PPD values calculated using the experimental results.

| | PMV | PPD (%) |
|---|---|---|
| Max. | 0.05 | 19.0 |
| Min. | −0.80 | 5.0 |
| Avg. | −0.30 | 8.2 |

### 3.2 Numerical Results

In order to compare the experimental measurements with the EnergyPlus simulations, the latter were made with the same experimental conditions on April 19, 2017. Figure 6 shows the average indoor temperature in the movie theater on April 19. The first increment of temperature starts with first session. The initial observed behavior, with a rapid increase in the temperature from 19.8 °C to 22.2 °C, is related to the heat released by the cinema theater users, alongside with the HVAC system being in the heating mode for a while, as the initial temperature was below the setpoint of 21 °C. However, when the average temperature reaches 23 °C, it is possible to verify a stabilization trend of the temperature that corresponds to the cooling setpoint of the HVAC system. Afterwards, a decrease of temperature occurs when the first session ends. This behavior is expected since at this moment people leave the room and, therefore, that heat source is removed and the outside temperature was lower. Then, the temperature increase again due to the beginning of the second session. Meanwhile, the second increase is not as sudden since there is a lower occupation rate and the exterior temperature in this time, from 18:50 to 21:00, is lower, increasing the heat losses to the exterior, and the HVAC system is in neutral mode as the temperature is bellow the 23 °C.

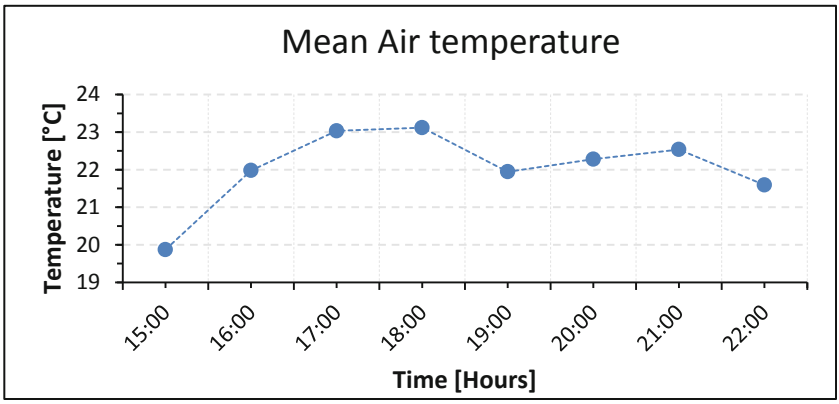



**Fig. 6.** Indoor air temperature.

Since the temperature is not the only determining factor of thermal comfort, it was necessary to compute the PMV and PPD indexes. The results are presented in Fig. 7.

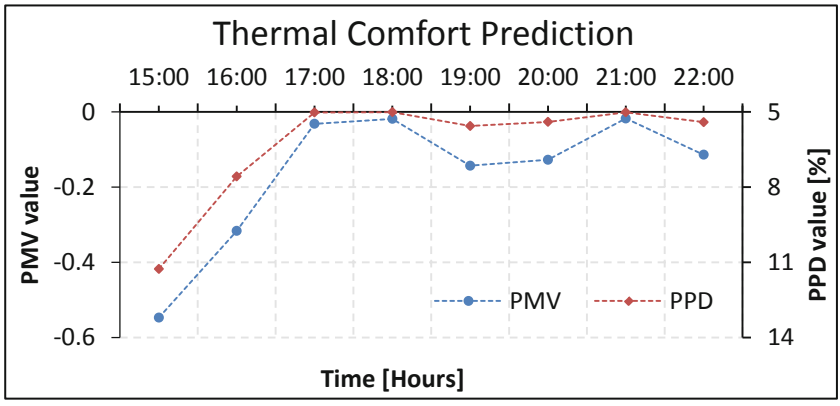



**Fig. 7.** PMV and PPV results from EnergyPlus.

In the present work, the remaining thermal variables (relative humidity and radiant temperature) do not change considerably and the comfort indexes follow the temperature pattern. While at the beginning, the thermal sensation trends to a cold sensation, due to initial HVAC heating mode condition and to the room occupancy, the PMV value quickly becomes close to zero, corresponding to a neutral/comfortable sensation.

Table 4 summarizes the results of the calculated comfort indexes, identifying the maximum, minimum, and mean values of the obtained indexes, alongside their differences with the experimental data. Through the comparison, it is possible to verify that the differences are small where the average PPD value does not surpass 2%.

These small differences may be related to the inherent error associated to the numerical methods, or even to the approximations considered in the problem definition. As for example, the thermal insulation values and the ventilation parameters measurements are susceptible to acquisition uncertainty and may even vary during the considered period, also, the HVAC system in the simulations was considered ideal with an initial heating mode and a rapid increasing temperature towards the setting point of 23 °C, which wouldn't probably occur with a normal HVAC system. Furthermore, EnergyPlus software calculates the thermal comfort indexes assuming the values in a middle point of the room while the experimental point (seat B8) had a different location, near the top back of the room.

**Table 4.** PMV and PPD values calculated within the EnergyPlus software and their respective difference with the experimental data.

| | PMV | | PPD (%) | | Temp. (°C) | |
|---|---|---|---|---|---|---|
| | Calculated | Difference | Calculated | Difference | Calculated | Difference |
| Max. | −0.02 | −0.07 | 11.3 | −7.7 | 23.1 | −1.4 |
| Min. | −0.55 | 0.25 | 5.0 | 0.0 | 19.9 | −0.1 |
| Avg. | −0.16 | 0.14 | 6.3 | −1.9 | 22.0 | −0.2 |

## 4 Conclusions

The objective of calculating the PMV and PPD by using the EnergyPlus was successfully met. The second objective was to verify if these results were similar to those obtained experimentally and it is concluded that despite some differences, they are similar. In the simulations, the cinema room has a thermal comfort between the neutral and the slightly cold with a low percentage of people dissatisfied. This result is also verified in the experimental data, although the PMV value is slighting more negative, probably due to the initial cold conditions. Despite this difference, the variation in the percentage of dissatisfied people is smaller than 2%. Usually, in HVAC systems, the setpoint temperature for cooling conditions is 25 °C instead of the defined 23 °C which explains the obtained cold sensations. Furthermore, this work allowed confirm that the occupancy rate is a determining factor to obtain a thermal comfort sensation. During most of the time, people do not provide the necessary energy to heat the cinema room. However, in the second session, this heat was enough. Additionally, the HVAC system is also an important factor to stabilize the temperature. As an improvement measure, the simulation should be repeated without considering an ideal HVAC system and the results checked, and experimental measurements should be made again in other cinema sessions and times of the year.

**Acknowledgments.** The authors would like to express their gratitude for the support given by FCT within the Project Scope UID/CEC/00319/2019 (ALGORITMI) and Project Scope UID/EMS/04077/2019 (METRICS).

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